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Agricultural Water Management Using Two-Stage Channels: Performance and Policy Recommendations Based on Northern European Experiences

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Abstract: Conventional dredging of ditches and streams to ensure agricultural drainage and flood mitigation can have severe environmental impacts. The aim of this paper is to investigate the potential benefits of an alternative, nature-based two-stage channel (TSC) design with floodplains excavated along the main channel. Through a literature survey, investigations at Finnish field sites and expert interviews, we assessed the performance, costs, and monetary environmental benefits of TSCs in comparison to conventional dredging, as well as the bottlenecks in their financing and governance. We found evidence supporting the expected longer-term functioning of drainage as well as larger plant and fish biodiversity in TSCs compared to conventional dredging. The TSC design likely improves water quality since the floodplains retain suspended sediment and phosphorus and remove nitrogen. In the investigated case, the additional value of phosphorus retention and conservation of protected species through the TSC design was 2.4 times higher than the total costs. We demonstrate how TSCs can be made eligible for the obligatory vegetated riparian buffer of the European Union agri-environmental subsidy scheme (CAP-AES) by optimising their spatial application with respect to other buffer measures, and recommend to publicly finance their additional costs compared to conventional dredging at priority sites. Further studies on biodiversity impacts and long-term performance of two-stage channels are required.

Keywords: two-stage channels; biodiversity; phosphorus; suspended sediment; water quality; drainage; agricultural water management; flood management; vegetation; CAP-AES

1. Introduction

In Boreal and Continental climatic conditions, an important aim for agricultural water management is the removal of excess water from the fields by drainage. Drainage ensures the good cultivation status of the soil and a sufficient load-bearing capacity of the fields to carry agricultural machinery, while preventing harmful compression of the soil. Artificially drained agricultural areas comprise 10–100% of the total agricultural land area in Northern and Central European countries and 25% in the USA and Canada [1]. In Finland, almost 90% of the field area requires drainage [2]. The field drainage consists of sub-surface drains beneath the soil surface or, more seldomly, of open field ditches laid in parallel across the field surface at a spacing of 10–50 m. The field drainage network discharges to larger ditches or to natural streams and rivers that have typically been dredged, straightened, and channelised to ensure adequate flow conveyance and sufficient drainage depth (Figure 1a).

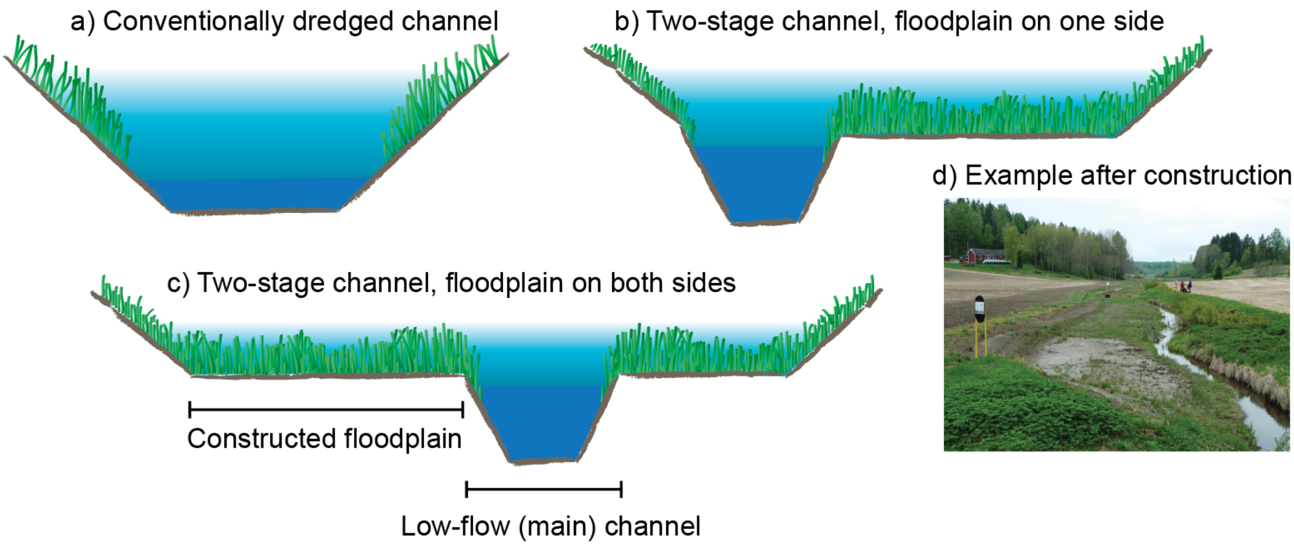

Figure 1. Typical cross-sections of (**a**) conventionally dredged trapezoidal-shaped channel and (**b**,**c**) two-stage channel, with (**d**) the Ritobäcken two-stage channel after construction. The dark blue refers to the water level at the mean discharge and light blue to the water level at high discharges.

Knowledge is accumulating on the harmful environmental effects of agricultural drainage (e.g., [3,4]). Drainage has drastically modified the natural cycling of water and substances in agricultural catchments (e.g., [5–7]) and has led to hydro-morphological alterations that severely impair stream and riverine ecosystems (e.g., [8,9]). Agriculture is the largest source of nutrient loading to water bodies in developed countries with efficient treatment of municipal and industrial wastewater: Fertilized fields contribute over 70% of nitrogen (N) and over 90% of phosphorus (P) loads in Europe (e.g., [10]). According to the European Union Water Framework Directive (WFD) [11], all water bodies in Europe, including agricultural rivers and streams, should reach good ecological and chemical status by 2021. This target remains widely unreached, and the deadline has thus been extended to 2027. Despite their negative effects and the WFD requirements, conventional drainage methods are mainstream.

Two-stage channel (TSC) design has been proposed as an alternative to conventional dredging to mitigate the adverse environmental impacts of drainage (e.g., [12,13]). Two-stage (compound) channels consist of constructed floodplains on one or both sides of the existing main (low-flow) channel (Figure 1b–d). TSCs are a nature-based solution since their design mimics the natural geometry of lowland streams that have a rather small main channel with adjacent frequently flooded floodplains. The TSC design aims at optimising the transport of both water and sediment [14] and thus at lengthening the life cycle of the channel by decreasing the required frequency of maintenance (e.g., [15]). The more natural-like geometry and flow conditions in the low-flow channel together with the new floodplain habitat are expected to contribute to enhanced ecological functioning and increased biodiversity, but studies on these aspects are very limited [16,17], while TSCs have been investigated predominantly from the viewpoints of urban flood management and morphological stability (e.g., [18–20]). Scientific research on the suspended sediment (SS) and nutrient retention in agricultural TSCs mainly covers Northern American conditions (e.g., [21,22]), with the exception of medium-term studies at one Finnish site (e.g., [23,24]) and a recent study at a Swedish site [25]. To our knowledge, agricultural TSCs have not been holistically reviewed, with previous studies largely neglecting the governance, financing, capacity, and farmers' acceptance aspects particularly in the European context [22,26]. Cost-benefit evaluations of TSCs [27] are needed to understand whether the benefits outweigh the reported higher construction costs compared to conventional dredging (e.g., [7,15]).

The TSC approach is a best management practice (BMP) for agricultural water management in several US states, whereas TSCs have not yet been systematically incorporated into the European Union Common Agricultural Policy (CAP). In Europe, the agri-environmental subsidy scheme (AES) of the CAP is an important tool to guide the farmers towards environmentally preferable measures, with approximately 90% of farmers in Finland participating in CAP-AES. CAP-AES has so far mainly aimed at improving farmland biodiversity and at reducing the loading of nutrients and harmful substances to water bodies (e.g., [28]). We argue that for aquatic ecosystems to reach a good status, the targets of improved water quality and enhanced riverine biodiversity should be linked together more holistically (see also [29]). In the European context, this requires better linking of the measures of CAP-AES to the targets of the WFD through the management of the agricultural channel networks.

Currently, edge-of-field buffers [30,31] are among the most widely applied agricultural water protection measures in CAP-AES. For instance, edge-of-field grassed filter strips (referred to as buffer strips in CAP-AES) between the sown area and the top of the channel bank are systematically applied along agricultural ditches and streams in Finland. However, a significant portion of the flow and loads bypass these buffers via sub-surface drains as edge-of-field buffer strips and zones treat mainly the local lateral surface runoff (e.g., [32]). By contrast, TSCs can be considered an after-field type vegetated riparian buffer (sensu [30]) which can treat both the lateral surface and sub-surface runoff as well as the loading from the upstream areas. We argue that a need exists for a better spatial targeting of the various vegetated buffers to improve the quality of agriculturally influenced aquatic ecosystems. Targeting has been called for in CAP-AES, but it has remained rather limited even though it noticeably improves the effectiveness of various nutrient control measures [33].

There is presently a strong initiative in Europe towards Nature-Based Solutions (NBS, e.g., [34,35]). This is reflected as a paradigm shift in agricultural water management principles in Finland. A new guideline for water management in agricultural and forestry areas by the Ministry of Agriculture and Forestry (MoAF, [36]) sets NBS as the default. Additional funding will be granted jointly by the MoAF and the Ministry of Environment in 2021–2023 for realising water protection projects. Presently, in one third of the drained arable area in Finland, the conveyance capacity and/or drainage depth are no longer sufficient due to the deterioration of the channel network [2], and actions are needed to ensure proper drainage. As EEA [34] points out, this is a good opportunity to 'think about green before investing in grey'.

The aim of this paper is to analyse the TSC design as a nature-based solution for agricultural water management in the Northern–Central European context. The specific objectives are to:

(1) Assess the key technical and environmental benefits of agricultural TSCs. The benefits were identified through a literature survey considering research under Boreal and Continental climates. Additionally, the performance of a reach-scale pilot site is demonstrated regarding flood mitigation, morphological stability, suspended sediment and phosphorus retention efficiency, and biodiversity indicators.
(2) Evaluate the total costs and monetary environmental benefits of the TSC approach in comparison to the conventional dredging. The pilot-scale results were scaled up to a larger agricultural catchment considering a 60-year time period.
(3) Investigate the bottlenecks in the financing and governance that are hindering the mainstreaming of TSCs. We provide recommendations on how to tackle the bottlenecks, including how to integrate TSCs into the CAP-AES based on their optimal spatial targeting with respect to other types of vegetated riparian buffers.

This paper is not intended to provide an exhaustive review of the efficiency and benefits of agricultural TSCs, as it is not appropriate considering the current technical readiness level (TRL) of the solution. Instead, we focus on the expected key indicators selected based on expert judgement and for which reliable information is available.

2. Materials and Methods

Table 1 provides a summary of the selected indicators and main methodologies used for analysing the TSC design approach. As study sites, we use a primary reach-scale pilot site, additional reach-scale pilot sites, and a catchment-scale pilot site, all located in Finland (see Supplementary Materials S1 and Table S1). Section 2.1 describes the TSC design approach and Section 2.2 the methodology for assessing the benefits of two-stage channels in comparison to conventional dredging, as well as the experimental investigations at the primary reach-scale pilot site. Section 2.3 explains the evaluation of the costs, financing, and monetary environmental benefits and Section 2.4 the analyses on bottlenecks in financing, governance, and capacity.

Table 1. The investigated indicators regarding two-stage channels.

Indicator	Assessment Criteria	Scale of Analysis	Main Methodologies
Benefits through ecosystem services	Adapted CICES 5.1 framework for comparing TSCs and conventional dredging	Boreal and Continental climates	Literature survey supplemented by field investigations and expert judgement (Section 2.2)
Water quality	Retention efficiency of suspended sediment and particulate phosphorus	Primary reach-scale pilot site	Field investigations (Section 2.2.1)
Drainage and flood mitigation	Water levels at different discharges, channel bed level development	Primary reach-scale pilot site	Field investigations, hydraulic modelling (Section 2.2.1)
Biodiversity	Abundance and species richness of plants and pollinating insects	Primary reach-scale pilot site	Field investigations (Section 2.2.2)
Costs and financing	Construction and maintenance costs, value of lost field and crops; shares of financing	Primary and supplementary reach-scale pilot sites (n = 6)	Collection of realised and estimated costs and financing (Section 2.3.1)
Monetary environmental benefits	Phosphorus retention, conservation of protected species	Catchment scale pilot site	Cost-benefit analysis based on up-scaled costs and additional environmental benefits (Section 2.3.2)
Bottlenecks in financing, governance, and capacity	Current CAP-AES, regional and national governance and legislation, knowledge gaps	Finland, generalisable to Boreal and Continental climates	Expert interviews (Section 2.4)

2.1. *Description of the Two-Stage Channel Design Based on the Reach-Scale Pilot Site*

The pilot reach-scale TSC (Ritobäcken, see details in Supplementary Materials S1) was designed and established by the regional water and environmental authority to demonstrate environmentally preferable agricultural water management. The channel was conventionally dredged several decades ago to improve drainage. As a result, significant bank and bed erosion had occurred in some of the steeper upstream reaches, while vegetation growth, siltation, and possibly compaction of the field soil had reduced the drainage depth and conveyance in the downstream reaches. To improve the drainage, a 4–5 m wide, 820 m long floodplain (Figure 2) was constructed in February 2010, with the TSC comprising ~1/7 of the agricultural main channel network; details of the design and construction are described by Västilä and Järvelä [13]. The aim of the design was to improve the conveyance in order to decrease the water levels caused by relatively frequent (less than 1-in-10-year) flow events, which would ensure the performance of the sub-surface drainage and decrease the flooding of the fields.

The TSC design was based on excavating a floodplain on one side of the channel at the estimated water level corresponding to annual mean discharge. In meandering reaches, the floodplain was constructed on the inner bends. The opposite bank was left intact, except for removing some large bushes. The bed and banks of the low-flow channel were not excavated, while excessive woody debris was removed from the channel bed to reduce the flow resistance. The site has been intensively investigated since the summer before the floodplain excavation (e.g., [13,23]).

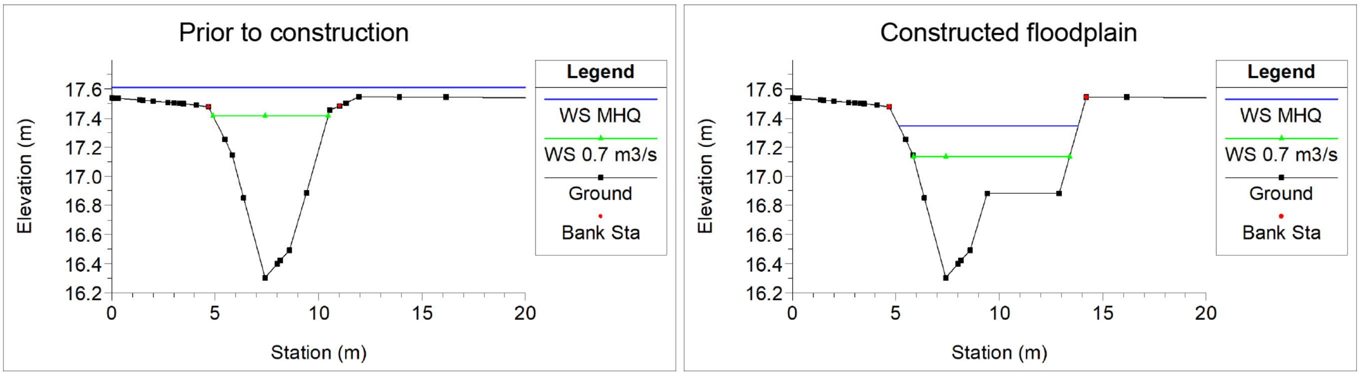

Figure 2. A representative channel cross-section before (**left**) and after two-stage channel construction (**right**), with simulated water surface levels (WS) at a 1-in-5 year flow (1.6 m^3/s) and a more frequent (0.7 m^3/s) flow event during spring conditions.

2.2. *Assessment of Technical and Environmental Performance and Benefits of Two-Stage Channels in Comparison to Conventional Dredging*

We adapted the CICES 5.1 framework ([37]) for describing the potential riparian ecosystem services provided by TSCs. The TSC design is an alternative to the conventional dredging of channels, and we focused on the additional benefits that can be achieved by the TSC design in comparison to the conventional dredging. The benefits were identified through a literature review focusing on TSCs in hydro-climatological conditions under which drainage is an important aim of agricultural water management (i.e., in Boreal and Continental climates). We compensated for the available limited research on TSCs by also practicing expert judgement and transferring evaluations of similar measures or circumstances, such as vegetated buffer strips, constructed wetlands, and stream restoration. The performance and benefits of the TSC design are demonstrated through our primary reach-scale pilot site, the Ritobäcken (Sipoo, Finland), which is, to our knowledge, the most thoroughly scientifically investigated agricultural TSC in Europe (see Supplementary Materials S1, [13,23,24,38,39]).

2.2.1. Analyses of Flood Mitigation, Morphological Stability, and Nutrient Retention at the Primary Reach-Scale Pilot Site

The mitigation of flooding and high water tables was evaluated based on the HEC-RAS hydraulic model version 5.0.7 [40] (Figure S1c). The topographical data representing the channel geometry before the TSC construction were obtained through real time kinematic satellite positioning (RTK-GNSS) by the designing consultant. The geometry of the TSC was obtained from the design plan (see [13]), with a typical cross-section shown in Figure 2. The investigated discharges were selected based on 2.5 years of continuous monitoring data covering both a dry and a wet year [23] interpreted with the help of a commonly applied region-specific empirical 'Nissinen' nomogram based on the size and shape of the catchment area, and the field and lake percentages [2]. We used the discharge of $Q = 0.5$ m^3/s, which corresponds approximately to the annual maximum autumn and late spring-early summer discharges, and $Q = 1.0$ m^3/s which corresponds to typical snowmelt discharges and to late autumn-winter discharges after long wet periods. The 1-in-5-year discharge was estimated at 1.6 m^3/s, while the maximum observed discharge during the 2.5-year monitoring was 1.5 m^3/s [23].

The flow resistance was expressed through Manning's n. We used one value for n for the entire study reach below bankful level, and the n values were derived based on previous experimental data from a 200 m long reach of the channel [23]. For the 'before construction' simulations, we used n values obtained for the main channel at flows just below floodplain level, with $n = 0.097$ under spring and $n = 0.111$ under autumn conditions. For the TSC simulations, $n = 0.08$ in spring and $n = 0.12$ in autumn conditions as experimentally determined at the highest floodplain flows with tall grasses and shrubs growing on the floodplain ([23], Figure S3). The differences in n represent the seasonal variation in the share of the wetted cross-section blocked by vegetation [23], with the TSC design increasing the share in the autumn when the grassy vegetation is erect and decreasing the share in the spring when the grassy vegetation is dormant and bent. We used n = 0.04 for the out-of-channel areas consisting predominantly of cropped fields with low stubble as the high flows occur outside the growing season. The flow is gradually varied and sub-critical, and the hydraulic modelling was conducted using steady discharge as the upstream boundary condition and normal water depth as the downstream boundary condition.

The data of Västilä et al. [23,38] were revisited to evaluate the effectiveness of the TSC design for retaining SS and particulate P, as well as for maintaining the drainage depth. The 2-year net deposition and erosion of SS were obtained from repeated high-resolution surveys of the channel geometry in six cross-sections ([23], Supplementary Materials S2) based on the measured dry bulk density of the deposits (480 g/m^3). The net deposition and erosion of P were obtained from the SS mass balance, as >90% of the deposited SS consisted of clay and silt fractions [23], and approximately 80–90% of the total P at high flows is in particulate form in such clayey catchments (e.g., [38,41,42]). We estimated the P content of deposited SS based on the strong linear regression (r^2 = 0.97, p < 0.001) between SS concentration (SSC, mg/L) and total P concentration (P_{tot}, µg/L) in water samples, with P_{tot} = 1.28 × SSC + 38 ([38], Figure S4). According to continuous monitoring of turbidity and flow at 5-min time steps together with site-specific turbidity-SSC regressions, SSC was 100–500 mg/L at most flows inundating the floodplain [23]. Furthermore, the P_{tot}–SSC regression indicated that these floodplain flows had a mean sedimentary P content of 0.11%, which was used for computing P balance in channel areas located at or above the level of the floodplain. The equilibrium sedimentary P content in the low-flow channel was assumed to be 10% lower (0.099%) due to a higher tendency for redox-dominated desorption in the permanently saturated sediments (e.g., [43]). For computing the retention efficiency, we used the total loads of the same period based on the continuous monitoring, resulting in the 2-year SS load of 220,000 kg [38]. The total P load was estimated from the SS load using the mean sedimentary P content of 0.11%, resulting in the 2-year TP load of 250 kg. The retention is expressed per year per kilometer of TSC length.

2.2.2. Field Investigations on Biodiversity at the Primary Reach-Scale Pilot Site

Vegetation and pollinating insects were investigated in summer 2020 as examples of taxa which may benefit from vegetated floodplains of the TSCs. The differences in the abundance, species richness, and species pool of plants and pollinating insects were studied between the primary reach-scale pilot site and an upstream conventionally dredged reference reach. The sites had a similar surrounding landscape structure (Figure S1), management, and distance to any hypothetical source area of plants to exclude the influence of these factors [44,45]. The dredging of the conventional channel was presumably conducted a longer time ago than the construction of the TSC, but this difference was expected to have negligible influence on the studied taxa since the TSC was assumed to have largely recovered from the disturbance in the 10 years that passed since the floodplain excavation. Thus, the main difference between the TSC and the conventionally dredged channel is the existence of the floodplain in the TSC.

The relative cover of all vascular plant species (no bryophytes or lichens were observed) was estimated as a percentage (1–100%), summing up to 100%, by 20 m long consecutive plots totalling 34 in the TSC and 28 in the conventionally dredged reference channel. In the TSCs, the floodplain and bank sections were estimated separately, whereas in the reference area, the whole bank from the water level to the field level was estimated as one section. Further reference data were obtained from nearby conventionally dredged channels: The presence of species in five consecutive 20 m long plots was studied 600 m upstream in Ritobäcken's Northern branch (Hälsängsbäcken, Figure S1) and in Immersbybäcken at a 5 km distance (catchment areas 242 and 574 ha, similar soil type as at Ritobäcken). Shannon's diversity index was calculated based on combined frequency and cover (mean cover $*$ relative frequency)$^{-2}$. Evenness (E) was computed as Simpson's Index of Diversity divided by the number of species R ($(1 - D)/R$, where D is Simpson's Index). The differences between the TSC and conventional dredging and between different channel parts were analysed with one-way ANOVA and Tukey's test.

In both the TSC and the conventionally dredged reference, pollinators were recorded within eight separate 50 m long study sections that were placed consecutively with a spacing of 50 m between adjacent sections. Thus, in both channels, pollinators were mapped along a 750 m long reach, with the studied plots covering a total length of 400 m along both channels. Butterflies, day-active moths, and bumblebees were surveyed using standardised transect counts [46]. Each 50 m transect was walked at a steady speed, and every pollinator observed within 5 m ahead and 2.5 m on either side of the surveyor was recorded. Pollinator abundance was separately determined for the floodplain and the buffer strip along the TSC by placing the transects so that they covered an equal width (i.e., 2.5 m) of these two habitat types. Each transect was conducted five times during the summer at 2-week intervals (ranging between 17 June and 14 August 2020) to cover the flight periods of the different species. The species richness and coverage of insect-pollinated plants in flower were recorded separately at the time of each transect count. Transect counts were carried out only in weather conditions when pollinators were actively in flight. The observations for the five counts were summed up for each species and the total abundances were used in the analyses.

2.3. Evaluation of Costs, Financing, and Monetary Environmental Benefits

2.3.1. Costs Based on Reach-Scale Pilot Sites

The unit costs of conventional dredging and the TSC design were estimated by considering the construction costs and financing, the maintenance and operation costs, the value of the lost field area, and the lost value of crop yields according to the vegetated buffer requirements of the current CAP-AES (Table 2). To represent the typical situation where the channel has been conventionally dredged in the past, we did not consider the initial construction costs for the conventional dredging. However, we computed the ratio between the construction costs of TSCs and the one-time hypothetical conventional maintenance dredging costs of the same reaches. Herein, maintenance refers to the common practice of removing the deposited sediment and the overlying vegetation by excavation, possibly accompanied with the cutting of the excessive aquatic weeds from non-excavated parts of the channel bed (e.g., [9]). Separate vegetation maintenance was not taken into account as it is not typically conducted in Finland (see also Section 3.3.1) and as vegetation maintenance costs are not expected to differ noticeably between the two channel designs. We assumed that the price of maintenance per meter of channel length is 50% lower for TSCs (Table 2) which are expected to be maintained through selective lowering of the floodplain, while underwater excavation of saturated sediments is needed for conventional dredging. Based on expert judgement, we used a maintenance interval of 20 years for conventional dredging required to maintain the fields in good condition by ensuring adequate drainage and preventing the flooding of fields. A maintenance interval of 50 years was used for the TSCs based on their expected 2.5 to 3 times longer life cycles (e.g., [15]; Section 3.1). No factors causing operation costs were identified.

Table 2. Methodology for the estimation of costs.

Cost Factor	Estimation Method for Two-Stage Channel	Estimation Method for Conventional Dredging
Realised construction costs and shares of financing	Personal communications with the leaders of the reach-scale pilot sites (Table S1)	No construction costs (channels have been constructed in the past)
Maintenance interval	50 years	20 years
Maintenance costs	Assumed 50% lower than for conventional dredging (2.5 €/m)	5 €/m (Mikko Ortamala, personal communication, 18 January 2021); realised costs at Uuhikonoja
Operation costs	Assumed negligible	Assumed negligible
Adjacent land value (lost field area)	Lost field area estimated from channel design plans; region-specific selling prices of 2019 (7800–11,400 €/ha) [47]	No losses in field area
Lost value of crops caused by lost field area	Typical crop yield of grains for Southern Finland (4 t/ha) [48]; present national selling price of grains (172 €/t) [49]	No losses in crops

2.3.2. Monetary Environmental Benefits at the Catchment Scale

We evaluated the total costs and selected additional monetary environmental benefits of the TSC channel design in comparison to the conventional dredging for a 255 km^2 agricultural-intensive catchment representative of the Baltic Sea region (Figure S5, Table S1). This river with significant biodiversity value and in need of dredging was selected to demonstrate the biodiversity benefits of TSCs. We assumed that approximately 20% (i.e., 14.8 km) of the agricultural channels in the catchment are converted into TSCs, with approximately 1-km-long two-stage reaches spatially targeted to the downstream ends of the largest ditches and smaller tributaries discharging to the river. The channel design was assumed equal to that at the reach-scale pilot site (Section 2.1). The total area costs were assessed by transferring the mean reach-scale cost data per metres of channel length (Table 2, Table S9).

The additional regional water quality benefits from the TSCs were assessed indirectly based on the efficiency of TSCs in improving P retention, amounting to 4.3 kg P/a/km of TSC reach length based on the results from the primary reach-scale pilot site (Section 3.2.2) with comparable clay soils in the agricultural areas. Based on the background data of the KUTOVA tool from Finnish conditions [50], the unit price for removed P of 249 €/kg P/year was used. This value is a rough and averaged estimation for similar types of measures as TSC (such as buffer zones or constructed wetlands) intended to control the nutrient leaching from fields and which can be assumed to produce other environmental benefits, e.g., for biodiversity similar to those that TSCs might also have.

The monetary biodiversity benefits were assessed indirectly based on the avoided environmental costs through the river's population of thick-shelled river mussel (*Unio crassus*), which is a strictly protected species in Annex IVa of the EU Habitats Directive. The small glochidium larvae are particularly sensitive to increased SS concentrations and siltation of the river bottom. We assumed that the river's mussel population will permanently decrease by 2% due to the conventional dredging of the main ditches and tributaries and that this loss can be prevented by the TSC design. This conservative estimate assumes that the conventional dredging is performed in as erosion-protective a manner as possible and that not all channels are dredged at the same time. We estimated the number of mussels using the median density of 9.9 individuals/m^2 from line dives carried out by the Southwest Finland ELY Centre [51]. We used the value of €50 per destroyed mussel assigned by the Decree on the Value of Protected Species by the Ministry of Environment [52]. According to the Nature Conservation Act [53], the deterioration and destruction of the breeding and resting places of *Unio crassus* is prohibited (e.g., [54]). Whosoever is guilty of such a violation, shall forfeit the monetary value of a protected plant or animal as a representative of its species [53].

We performed calculations for a time frame of 60 years as we assume that drainage is needed in Boreal waterlogged soils during this century despite climate change. The net costs were evaluated by adding the environmental benefits (positive) to the total costs (negative). The equivalent annual cost (EAC)—an annual cash flow over the duration of the project—was estimated using a 5% interest rate for discounting maintenance costs and a lower interest rate of 2% to measure the present value of environmental benefits. Due to the uncertainty in the estimates used in the calculation, the persistence of the final result was assessed using a light sensitivity analysis which changed all initial values by ±20%.

2.4. Analyses of Bottlenecks in Financing, Governance, and Capacity

To collect the key bottlenecks in financing, governance, and capacity related to the implementation of TSCs, we revisited the material of [55], who assessed the implementation of NBS in the Finnish agricultural drainage projects that are publicly subsidised through the Centres for Economic Development, Transport and the Environment (ELY centres). Seven civil servants representing five ELY centres assessing the funding applications and/or environmental aspects of the drainage plans were interviewed following a template with 20–25 questions [55]. The semi-structured interviews were conducted and recorded in summer 2020, and the material was thematically analysed.

3. Results

3.1. Benefits of Two-Stage Channels in Comparison to Conventional Dredging

In this section, we identify the key benefits of TSCs based on the adapted CICES (5.1) hierarchical structure [37]. While both conventionally dredged trapezoidal-shaped channels and TSCs mitigate floods, support the field drainage, and have vegetation on the banks, Table 3 summarises the additional benefits of TSCs. These benefits are mainly generated through the nature-based features of TSCs, which mimick the geometry of natural lowland streams, whereas the conventional dredging produces straight, trapezoidal-shaped channels with overwide beds (Figure 1). Specifically, the TSC design re-establishes a connection between the main channel and floodplain, allowing frequent inundation of the floodplains, whereas such a connection exists in the conventionally dredged channels only during exceptionally high flood flows. In addition, TSCs exhibit a greater abundance of vegetation in contact with the flow at medium to high flows and a more natural-like geometry and flow conditions in the low-flow channel, including a narrower bed sustaining the flow also during low to medium discharges (Figure 1).

Table 3. Potential key benefits of two-stage channels in comparison to conventional dredging as adapted from the CICES (5.1) hierarchical structure [37]. Text EXP refers to expert judgement of the authors.

Section and Division	Code and Simple Descriptor	Potential Benefits of Two-Stage Channels (TSCs)
Regulation and Maintenance: Transformation of biochemical or physical inputs to ecosystems	2.1.1.1 Bio-remediation and filtering of wastes by micro-organisms, algae, plants, and animals 2.1.1.2 Chemical and physical processing of wastes 5.1.1.3 Mediation of waste, toxics, and other nuisances by non-living processes	More vegetated surfaces trapping more suspended sediment (this study (Section 3.2.2), [23,56]) and particulate phosphorus (this study (Section 3.2.2), [21,56]) from the fields during floods Conventionally dredged streams remove little nitrogen [57], while floodplains enhance nitrogen removal through intensified denitrification [22,58,59] Conventionally dredged stream beds retain little dissolved phosphorus [57], while floodplains retain more dissolved phosphorus [56,60] Decreased turbidity at high flows [59,61] Vegetative uptake of nutrients higher in TSCs due to larger vegetative biomass EXP

Table 3. *Cont.*

Section and Division	Code and Simple Descriptor	Potential Benefits of Two-Stage Channels (TSCs)
Regulation and Maintenance: Regulation of physical, chemical, and biological conditions	2.2.1.1 Controlling or preventing soil loss	Protection of bank erosion since the banks are lower and the floodplain banks do not collapse into the low-flow channel EXP
	2.2.1.3 Regulating the flows of water in our environment	Long-term functioning of drainage since the TSC bed is self-cleansing and seldom needs maintenance (this study (Sections 3.2.1 and 3.3.1), [12,62]) Likely long-term reduction of flood risks in the fields with less maintenance needs [12,63] Higher baseflow and dry-season water levels due to narrower low-flow channel EXP
	2.2.2.1 Pollinating our fruit trees and other plants	Floodplains offer additional habitat for pollinators and may be important nectar sources in dry years (This study (Section 3.2.4))
	2.2.2.3 Providing habitats for wild plants and animals that can be useful to us	Floodplain increases plant biodiversity, particularly the number of wetland species (this study (Section 3.2.3), [64]) Larger fish diversity [16] Support for protected fish species through more natural-like main channel geometry and flow conditions allowing habitat restoration [65] Macroinvertebrate communities likely benefit from improved connectivity to floodplain [17]
Cultural: Direct (or indirect) interactions with living systems that depend on (or do not require) presence in the environmental setting	3.1.1.2 Watching plants and animals where they live; using nature to destress	Landscape and recreational benefits for local residents through the more variable landscapes EXP
	3.1.2.1 Researching nature	Allows increasing knowledge about the biophysical characteristics or qualities of species or ecosystems associated with nature-based solutions for agricultural or riverine water management EXP
	3.2.2.2 The things in nature that we want future generations to enjoy or use	Non-use values from preserving endangered species, habitats, and agricultural landscapes EXP

The evidence supports the hypothesis that TSCs reduce siltation of the channel bed and are therefore likely to decrease the need for maintenance and to increase the channel life cycle. In conventionally dredged channels, the channel bed silts up and overgrows more easily, causing a greater need for management dredging, whereas the low-flow channel of a well-designed TSC is self-cleansing [12,15,62]. For instance, chemical or mechanical removal of woody and broadleaf vegetation has been the only routine maintenance activity required in TSCs in Midwest US in the first 10–15 years after their construction [63]. The reduced need for maintenance is explained by the fact that TSCs mimic natural conditions in terms of natural sedimentation and flooding processes [63]. Properly designed TSC geometry functions hydraulically at low, medium, and high flow conditions, providing both sufficient flood capacity and higher water levels at low flows. However, the oldest of these agricultural TSCs have been functioning for around 20 years. Thus, little is known about their long-term stability or other performance metrics under the typical conditions with high agricultural SS input.

TSCs appeared to provide water quality benefits due to the retention of SS and P on the floodplain (e.g., [21,23]). To the authors' knowledge, the best performing TSC reduced the loads of SS and total P by 22–40% and 40%, respectively [56]. TSCs have been found to decrease the concentrations of N by removing it through intensified denitrification [58,59]. By contrast, conventionally dredged ditches with short residence times provide only limited removal of dissolved P and N [57]. The retention and removal of nutrients and SS improves the water quality in the channel itself but also decreases the loads to downstream water courses. However, notable variation in performance has been observed, with several TSCs showing higher concentrations than conventionally dredged reference reaches (e.g., [21]). As a further limitation and source of uncertainty, an experimentally obtained annual to longer term mass balance for SS or nutrients is available for only a few sites, while the processes in the low-flow channel are typically not well taken into account in the investigations (e.g., [39]). Overall, the effect of TSCs and other NBS or management actions on water quality are not fully understood in Boreal channels where the cycling of P and N can notably differ from warmer climates due to freeze–thaw cycles [66], the influence of the ice cover on flow and transport of both soluble and particulate compounds [67], and the uncertainty regarding the efficiency of microbial transform processes at low temperatures [68].

The limited evidence available suggests that TSCs likely have positive effects on biodiversity. According to our field studies (Section 3.2.3), the TSC design showed larger plant biodiversity than conventional dredging. In addition, [16] found that agricultural TSCs improved riparian and instream habitat quality, as evidenced by a greater species richness of fish and higher percentages of gravel-spawning fish than in conventional ditches. The connectivity to floodplains is an important driver for fish and macroinvertebrate communities [17]. In addition, other methods of environmentally preferable hydraulic engineering or stream restoration can be more reliably implemented in TSCs than in conventionally dredged channels due to the more natural hydro-morphology, allowing, e.g., the restoration of spawning gravels (e.g., [65]). Overall, the ditch network within cultivated catchments provides a wide range of ecosystem services, while also mitigating herbicides and supporting pollination and pest control functions [1]. Rowinski et al. [7] reviewed the influence of riverine vegetation on water flow, river morphodynamics, transport and mixing processes, water quality and stream ecology, while Riis et al. [69] provided an overview of regulating and maintenance services provided by riparian vegetation.

3.2. *Performance of the Case Study Two-Stage Channel*

3.2.1. Mitigation of Flooding and High Water Tables

According to the model simulations, the TSC design notably decreased the flooding of the fields and thus improved the drainage compared to the pre-construction situation representing a previously dredged but non-maintained channel (Figures S6 and S7). The TSC design decreased the water levels at discharges higher than the mean (i.e., during flows inundating the floodplain). Discharges lower than the mean were not affected since the low-flow channel was not modified in the TSC construction. The largest effects were obtained just below bankful flows when the full flow capacity of the floodplain was in use. The TSC design improved the flow conveyance, with approximately 50–100% higher discharges conveyed at a given water level compared to the pre-construction situation. The water levels decreased by up to 20 cm during autumn conditions and by over 25 cm during spring conditions when the flow resistance of the TSC was lower since the floodplain vegetation was dormant. We recognise that uncertainties exist in the estimated water levels of the pre-construction situation due to the extrapolation of the flow resistance to higher flows (Section 2.2.1). This extrapolation is commonly practiced in hydraulic modelling but should be replaced by the development of more physically based methods (e.g., [70]). Nevertheless, the modelling results agreed with the observations of the landowners regarding the significant reduction in flooding and harmfully high water tables after TSC construction.

According to the repeated cross-sectional surveys (Supplementary Materials S2), the TSC design prevented the aggradation of the low-flow channel. During the 2 years after floodplain excavation, a net loss of sediment occurred from the low-flow channel, with the level of the main channel bed decreasing by 2.6 cm/a (standard deviation of 2.0 cm/a). Thus, the TSC appeared capable of flushing the sediments deposited in the channel bed after the last conventional dredging several decades ago. The results indicated that the constructed TSC had good self-cleansing capacity and can therefore likely maintain adequate flow conveyance and drainage depth in the long term. The morphological stability was assessed as good due to the low net changes in vertical soil elevation in different cross-sectional parts of the channel [23].

3.2.2. Retention of Suspended Sediment and Phosphorus

Based on the 2-year cross-sectional data (Supplementary Materials S2, [23]), the floodplain retention in the TSC averaged 15,000 kg SS/a/km and 17 kg P/a/km, with the retention efficiency of 13.6% for SS and 16.3% for P per km of TSC length. Due to the re-suspension of sediment from the bed of the low-flow channel (Section 3.2.1), the total net retention considering the entire cross-sectional area was lower at 2400 kg SS/a/km and 4.3 kg P/a/km, with the retention efficiency of 2.1% for SS and 3.5% for P per km of TSC length. We expect the re-suspension rate from the low-flow channel to notably decrease with time, as the loose deposits originating after the last conventional dredging have been flushed away [39]. Thus, over a longer time span, the net retention percentages of SS and P are expected to increase in comparison to these first 2–2.5 years after floodplain excavation. Assuming that the re-suspension from the main channel reduces to half results in medium-term P retention of ~12 kg or 10% per km of TSC length. However, this figure cannot be used as the efficiency of the TSC as there is P retention also in conventionally dredged channels undergoing bed deposition. While we lack a reference reach that would have been conventionally dredged at the same time, TSCs comparable to our conditions have shown on average 6–10% lower soluble reactive P and total P concentrations per km of TSC length compared to conventionally dredged reference reaches [61], while [59] report 23% reductions in soluble reactive P for reaches with a 400 m average length. We obtained particulate P retention of ~0.25% per each percentage point of the agricultural channel network length consisting of two-stage geometry. In a US watershed, the conversion of conventional channels into TSCs resulted in the corresponding figure of 0.5% for total P [71]. Considering that our results represent mostly the particulate fraction constituting 80–90% of TP (see Section 2.2.1), our P retention in the first 2 years after TSC construction (3.5%) corresponded well to the reported efficiencies of TSCs, and thus we used the corresponding retention of 4.3 kg P/a/km for scaling up to the catchment level (Section 2.3.2).

3.2.3. Plant Biodiversity

The highest number of plant species was recorded in the TSC and the second highest on the TSC floodplain and TSC bank sections counted separately, while all three conventionally dredged reference areas had lower numbers of species (Table S2, Figure 3a). Species richness in the studied 20-m-long plots showed similar patterns, with the plots in the conventionally dredged sections having, on average, the lowest number of species (Table S3). The differences between the bank and floodplain, as well as between the banks and the conventionally dredged channel, were statistically significant (one-way ANOVA and Tukey's test), but the differences between the floodplains and the conventionally dredged channel were not. The TSC appeared to be beneficial to herbs favouring moist or wet conditions (Supplementary Materials S3). Richness in both the floodplain and bank could be due to the proximity of the wider and more uniform flooded section, i.e., the man-made floodplain: Some species 'creep' up the bank. Conversely, in the conventionally dredged channel, the vegetated area extends to the water level in the ditch, yet wetland species were few.

All study channels had some species that were not recorded elsewhere, but the number of species that were recorded either only in the banks or the floodplains or in both was distinctly higher in the TSC than in the reference channels (Figure 3a). In Ritobäcken, 41% of the species were common to the conventionally dredged and two-stage bank and floodplain, 40% of the species were recorded only on floodplain and/or banks, while only 8% of the species were unique to the conventionally dredged channel (Figure 3b). Shannon's diversity index indicated a rather high diversity for all Ritobäcken sections, but the lowest diversity for the conventionally dredged channels. Evenness was lowest on the floodplains, as expected from the number of relatively frequent dominant species (Table S4).

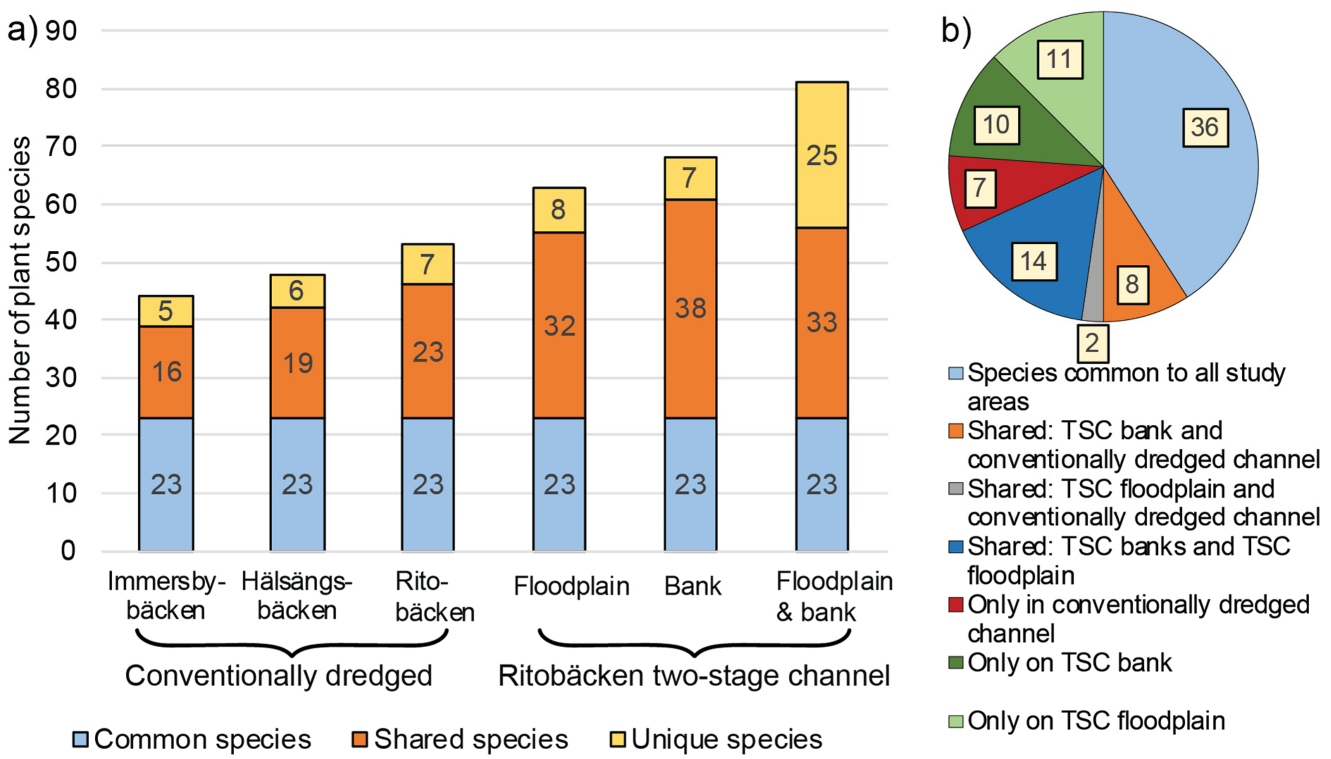

Figure 3. (**a**) Number of plant species in the three conventionally dredged channels and the Ritobäcken TSC. Common: Species found in all channels; shared: Species found in two to four channels; unique: Species found in one channel. (**b**) Number of species on the TSC banks and floodplain and in the conventionally dredged channel of Ritobäcken.

3.2.4. Diversity of Pollinating Insects

Pollinator counts showed that various kinds of wild pollinators, as well as honeybees, are relatively abundant along both kinds of studied reaches (see Supplementary Materials S4, Tables S5 and S6). We did not detect any systematic differences between the two-stage and conventional channels in terms of pollinator species richness and abundance (Figure 4, Table S7). The average number of flowering nectar plant species groups was significantly higher in the TSC than in the conventional channel (Table S7), and probably reflected the functioning of the floodplain as an additional habitat type provided by the TSC. Most pollinator variables did not correlate significantly with the number of flowering nectar plant species groups. However, bumblebee species richness was positively correlated with flowering nectar plant species richness (Pearson correlation coefficient $r_P = 0.51$; probability $p < 0.05$, $n = 16$), and bumblebee abundance also showed a tendency for a positive correlation with nectar plant species richness ($r_P = 0.43$; $p < 0.10$, $n = 16$). Along the TSC, the pollinators were systematically more abundant in the buffer strip than on the floodplain (Figure 4, Table S8), which was likely caused by the notably larger coverage of flowering nectar plants in the buffer strip than on the floodplain. Despite this difference, our study confirmed that flowering nectar plants grow on the floodplains of TSCs and that they are visited by pollinators.

3.3. Costs and Monetary Environmental Benefits

3.3.1. Costs at Reach-Scale Pilot Two-Stage Channels

The construction costs of TSCs were highly variable and depended on the length of the constructed channel and on the excavated soil volume (Table S9). The average construction cost was 24,000 € with the average TSC length of 980 m. Unit costs of TSC varied at 11–35 €

per metre of channel length (average 21 €/m) and at 3.1–8.4 € per m^3 of the excavated and removed soil mass (average 5.2 €/m^3). The construction cost ratio (Table S9) indicated that the construction of TSCs was, on average, four times more expensive than the one-time conventional maintenance dredging. This is in line with [15], who estimated the difference to be 3–4-fold. The difference arose largely from the fact that the amount of soil that must be excavated and transported away is much larger for the TSC construction than for re-dredging of the existing ditches [7,12]. The value of lost field and the annual value of lost crops averaged 3.6 and 0.25 € per channel metre, respectively (Table S9).

According to [72], no or only small-scale vegetation maintenance had been conducted at three of our pilot sites in the first decade after TSC construction, which is in line with the observations that TSCs do not require as extensive and frequent maintenance as conventionally dredged channels (Section 3.1). Our cost estimates did not take into account the surveying, channel design or supervision, which may generate slightly higher costs for TSCs compared to conventional dredging. If TSCs are constructed below bridges, the bridges must be somewhat longer compared to a conventionally dredged ditch, but this cost is typically eliminated by leaving short conventionally dredged reaches upstream and downstream of bridges or culverts.

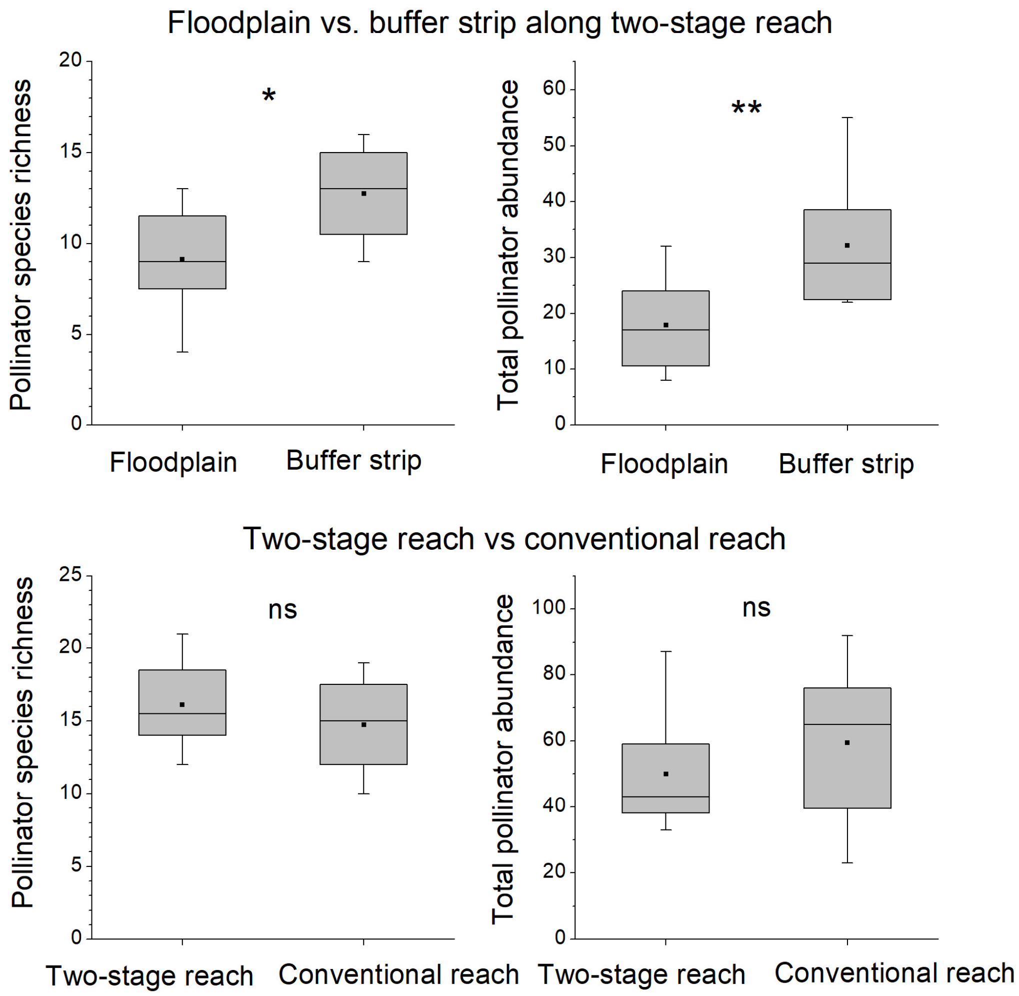

Figure 4. Comparison of total pollinator species richness and total abundance between the floodplain and the buffer strip along the TSC (**upper** panels) and between the TSC and conventional dredging (**lower** panels). The boxes show median and first and third quartile values. Means are indicated by small black dots, and minimum and maximum observed values by error bars. * $p < 0.05$, ** $p < 0.01$, ns $p > 0.05$.

3.3.2. Total Costs and Monetary Environmental Benefits Scaled up to a Larger Catchment

At the catchment scale, the TSC design was estimated to generate a total additional environmental benefit of approximately 1.5 million € over the 60-year period at present value, corresponding to a net benefit of 0.9 million €, whereas conventional dredging generated a net cost of 222,000 € (Table 4). Measured through equivalent annual cost (EAC), the discounted net benefits of the TSCs were approximately 7400 €/year, while the conventional dredging resulted in 1200 €/year net costs. The monetary benefits of the TSC design associated with the improvement in water quality through P retention were somewhat larger than the biodiversity benefits through saved individuals of the rare river mussel population. The result of no environmental benefits obtained with the conventional dredging reflects the applied estimation method based on the additional benefits of TSCs.

Table 4. Comparison of costs and selected additional environmental benefits of the TSC design at the catchment scale in a 60-year period in comparison to the conventional dredging (present situation with the TSC design not incorporated into CAP-AES).

Variable	Units/Unit Cost	Conventional Dredging	Two-Stage Channel Design
Project life	years	60	
Channel length	km	14.8	
Maintenance interval	years	20	50
Maintenance costs	€5/€2.5 per channel metre	−222,000	−44,000
Construction costs	€0/€21.2 per channel metre	0	−314,000
Adjacent land price	€0/€3.6 per channel metre	0	−53,000
Lost crop value	€0/€0.25 per channel metre	0	−223,000
Environmental benefits for biodiversity	€50 per *Unio crassus* mussel	0	594,000
Environmental benefits for water quality	€249 per phosphorus kg	0	951,000
Net costs in 60 years	€	−222,000	910,000
Equivalent annual net cost (EAC)	€ per year	−1200	7400

The maintenance costs dominated for conventional dredging, whereas the construction costs dominated for the TSC design. The construction and maintenance costs of TSCs were 1.6 times higher compared to dredging in the 60-year period. While the construction costs of TSCs are large, they are realised only once, with the subsequent maintenance costs estimated to be 14% of the initial construction costs (Table 4). The lost crop value according to the vegetated buffer requirements of the present CAP-AES generated 35% of the total costs of TSCs.

The sensitivity analysis showed that the greatest effect on the difference in equivalent annual cost between conventional dredging and TSCs was created by the unit cost of P retention (21%), the size of the mussel population (13%), and the TSC construction cost per metre (12%). We note uncertainties associated with the P retention due to the lack of available data to verify the similarity between the channel sediments at the reach-scale and catchment-scale pilot sites.

3.4. *Current Financing Situation and Bottlenecks in the Agri-Environmental Subsidy Scheme*

The shares of financing of the investigated TSCs are reported in Table S9. The differences in financing illustrate the absence of a systematic nationwide approach for financing TSCs. The farmers' share of the costs was rather low in the six pilot studies, averaging less than 10%. Most financing has been arranged through individual, externally funded research and development projects. Currently, in Finland, a TSC project may obtain state financial support in the form of either a drainage subsidy from Agrifood Research and Development Fund (MAKERA) managed by the ELY Centers (Regional State Authority) or from CAP-AES's non-productive investments as wetland investment and maintenance allowance. However, overlapping subsidies cannot be received for the same drainage area. Support can cover no more than 40% of the costs, but environmentally friendly (i.e., nature-based) solutions, and particularly expensive structures, may increase the support percentage. In recent years, MAKERA has granted approximately 2.5 million €/year of state support for about 50 dredging projects.

According to the expert interviews [55], the current compensation system in Finland does not adequately cover the additional costs of NBS to the landowners. The interviewees pointed out that the budget for the non-productive investments of CAP-AES has been very limited during the current programme period. While non-market benefits, such as improved biodiversity and water quality, can be achieved through nature-based methods, the interviewees stated that landowners are most likely unwilling to pay that much extra for their implementation. Despite the possible long-term benefits for crop growth and income levels, farmers often prefer conventional dredging methods over NBS. The costs associated with the lost crop value following TSC construction (Table S9 and Table 4) largely resulted from the cross-compliance requirements of the present CAP-AES. Despite the presence of an after-field type buffer provided by the excavated, vegetated floodplain, edge-of-field buffer strips with a minimum width of 1 m along ditches and 3 m along streams are required on both sides of TSCs. Since the top widths of TSCs are larger than those of conventionally dredged channels, the TSC construction typically reduces the arable land area that is entitled to area subsidies. In addition, channels with a top width smaller than 3 m are considered in the subsidised field area as for them the field area is defined to start from the channel centreline, which is a disincentive towards the wider TSCs.

Due to the low profitability of farming and the low income level of farmers, the CAP-AES subsidies have a critical role in ensuring adequate income levels for farmers in Finland. According to the interviewees, farmers may be unwilling to establish TSCs due to the negative impacts on income support and crop production. As a further bottleneck of the current CAP-AES, a decrease in field area as a result of TSC construction will result in the farmers losing both the areal and the buffer zone support from the whole 2015–2022 programme period regarding those areas that will be decommissioned. Together with the low income level, the need for long-term commitment appeared to hinder the farmers' willingness to invest in NBS.

3.5. Development Needs of Governance to Boost Nature-Based Solutions

The interviews of the Finnish ELY centre officials (Section 2.4) revealed several development needs. The authorities granting the financial support for nature-based projects should have more systematic ways for communication and information exchange both within and between departments and organisations. In addition, the management of relevant information (forms, receipts, etc.) should be more effective and achievable by all in need. The information should be preferably in electronic format. With these improvements, the expertise and knowledge from prior related projects and decisions would be available for all involved in the decision-making process and the process itself would be more effective and comprehensive. Well-functioning information systems could, for example, promote the consideration and use of alternative forms of financial assistance provided by authorities of different areas in projects involving NBS [55].

According to the interviewees, the practice of leasing farmland, which is common in Finland, should be developed to encourage long-term investments, as also pointed out by [36]. The typical short contracts decrease the willingness of leaseholders to commit to larger investments that would improve soil quality and crop growth. In Sweden, Ref. [73] found that farm owners were significantly more willing than leaseholders to create wetlands on their farms. The authors inferred that such expensive and long-term commitments may seem challenging and risky for leaseholders who might have contracts for only 1–5 years.

In order for the NBS to be viable for financial aid in Finland, an acceptable plan of the project has to be provided. According to the Act on Support for Drainage Operations [74], aid can be allocated to such design costs. However, in the case of a negative grant decision, the design costs are not compensated either. This might be a financial risk the farmers are not prepared to take. For this reason, assisting the planning phase would facilitate the start-up of projects and the preparation of aid applications.

4. Discussion

4.1. Potential of Two-Stage Channels for Decreasing the Harmful Hydro-Environmental Impacts of Agriculture

Based on the available studies, agricultural TSCs appeared more beneficial than conventional dredging regarding water quality, stream and riparian biodiversity, and long-term maintenance of the drainage and flood mitigation functions (Table 3; Figure 5). While farmers profit from the well-functioning drainage and flood mitigation through improved crop yields, the environmental benefits are enjoyed collectively at local, regional, and national scales depending on the extent of implementation of the TSC design. The retention and removal of suspended sediment, phosphorus, and nitrogen (e.g., Sections 3.1 and 3.2.2) improves the water quality both in the channels and in downstream water bodies, benefiting those using these water bodies, e.g., for recreation. The benefits to biodiversity and water quality likely help achieve the local WFD targets. The large-scale application of TSCs could contribute to complying with the national and international agreements on reduction of nutrient loading to the Baltic Sea, such as the Baltic Sea Action Plan of Baltic Marine Environment Protection Commission (HELCOM). While water quality can be best enhanced using a combination of various field- and catchment scale measures, including, e.g., constructed wetlands, improving the stream biodiversity and drainage typically require measures targeting the channel network itself.

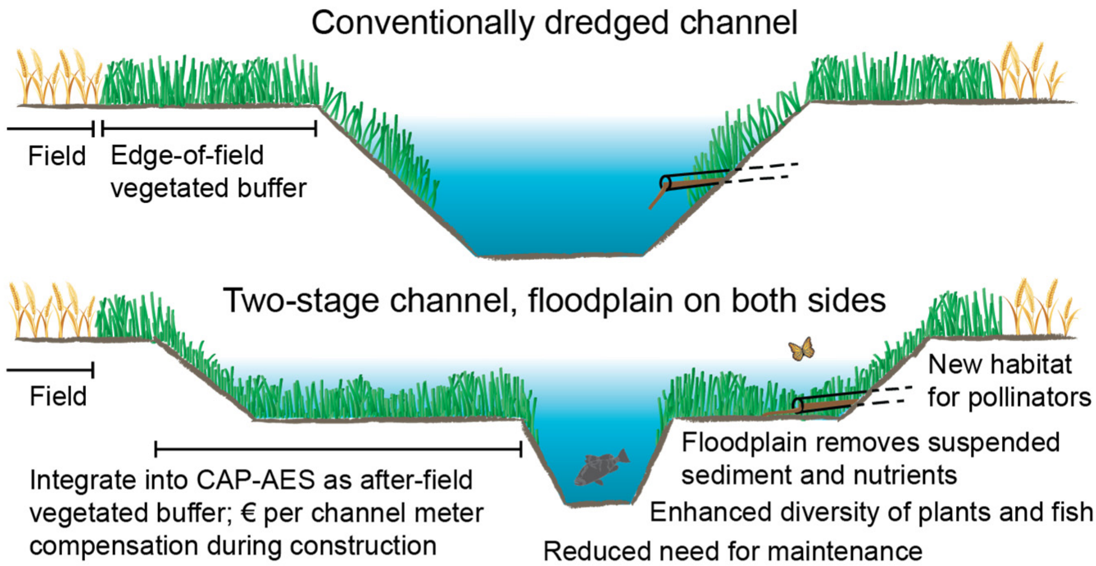

Figure 5. Benefits and the proposed integration of two-stage channels into CAP-AES. Optional sub-surface pipes draining the fields are also shown.

As one of the first investigations on the biodiversity effects of TSCs (see also [16,25]), we found relatively species-rich plant and pollinator communities along the TSC. Plant species richness was at least 30% higher along the TSC than along conventionally dredged channels, whereas the species richness or abundance of pollinators did not differ between the two kinds of channels. Higher plant diversity along the TSC was due to a number of plant species with preferences for wet habitats—these were only observed on the TSC floodplain. Thus, excavated floodplains enhanced the riparian plant biodiversity, with TSCs potentially having beneficial effects on any plant-dependent taxa. By contrast, edge-of-field buffer strips harbour a low number of wetland species (e.g., [64]) and the usual agri-environment schemes do not necessarily have positive effects on plant biodiversity [75]. The wet habitat plant species did not seem to attract pollinators, which, in turn, strongly concentrated on flowering plants of a drier habitat. However, the floodplains offer some additional habitat for pollinators and may be more important nectar sources in years when flowering nectar plants on field margins suffer from droughts, but no significant drought periods occurred during our study.

The TSC design is widely applicable to small and medium-sized ditches, brooks, and streams particularly under Boreal and Continental climates requiring efficient drainage and flow conveyance. Based on the investigations under Northern European and Midwestern United States conditions, TSCs appeared to be well suited to lowland and mildly sloping areas with clayey to sandy soils. The TSC design is particularly favourable for channels having high biodiversity values or where conventionally dredged channels are unstable or require frequent clean-outs (Table 3, [14,76]). Our example species, *Unio crassus,* is rare but relatively more frequent in the rivers in Southern Finland that need maintenance [54]. The original trout (*Salmo trutta*) and its local strains are other examples of protected species that likely suffer from conventional dredging (e.g., [65]). Protecting such rare in-stream species urgently requires more sustainable solutions than conventional dredging and we recommend constructing TSCs at targeted locations. Based on the literature survey, we expect measurable benefits if TSCs cover a minimum of ~10–20% of the excavated reach length.

Climate change increases the need for efficient drainage, flow conveyance, and new methods for controlling agricultural loading since the amount of precipitation and the leaching of SS and nutrients from fields is expected to rise in the Boreal zone (e.g., [77]). The need to maintain the agricultural channel network in Central and Eastern Europe is extensive (e.g., [1]), with thousands of kilometres of channels in need of maintenance in Finland alone (e.g., [2]). As an after-field type vegetated buffer capable of treating both the local lateral runoff and the loading from the upstream areas (sensu [30]), the TSC design likely provides water quality improvements in sub-surface drained areas where the drain flows bypass the edge-of-field buffers (e.g., [32]). Northern and Central Europe have plenty of potential sites for implementation of TSCs, as around 80% of the field area is sub-surface drained [1].

TSCs, as a nature-based engineering solution, address the emerging ecological paradigm proposing that ecosystems should be managed for adaptive and functional integrity rather than attempting to restore them to an idealised conception of the natural state (e.g., [78]). We argue that this is particularly true in the strongly modified drained agricultural landscapes (e.g., [7]). In these human-impacted areas, '*a stream can be considered restored if it is able to maintain that state and function without continual management input to resist the agricultural disturbance, and also through providing enhanced ecosystem services*' [29]. Based on the available evidence (Table 3), the TSC design seems to fulfill this criterion in comparison to conventional dredging.

4.2. Proposed Financing Reform Based on Optimal Targeting of Two-Stage Channels and Re-Direction of Public Funding

In this section, we propose how the present policy and financing framework (Section 3.4) could be developed to promote the implementation of TSCs. This appears justified as their monetary environmental benefits are larger than the associated costs (Section 3.3.2). Table 5 presents a simple financing model for small TSCs, considering 1 km of channel length over a 60-year time frame based on the mean values of the investigated 4–40 km^2 reach-scale pilot sites (Tables S1 and S9). Our model is based on the premise that the beneficiary pays for the benefits. As the farmers profit from the well-functioning drainage, they will cover the associated costs which can be approximated by the costs of conventional dredging. Most of the expected environmental benefits of TSCs for nature and people (Table 3) are ecosystem services and public goods (see, e.g., [35,69,79]), for which monetary markets are lacking or are not direct and obvious. Thus, the farmers have very little interest in constructing TSCs if they need to pay more than for conventional dredging.

Table 5. A financing model for two-stage channels over a 60-y time frame for 1 km of channel length (see details in the text). The model is based on the additional costs and benefits compared to conventional dredging.

Associated Cost Factor	Costs (€) of Conventional Dredging	Costs (€) of Two-Stage Channel (TSC) Design	Notes
Maintenance costs	−15,000	−3000	Lost crop value computed assuming the proposed CAP-AES reform (3 m of TSC width replaces the required edge-of-field buffer strips; Figures 5 and 6)
Construction costs	-	−21,200	
Adjacent land value	-	−3600	
Lost crop value	-	−2800	
Total costs	−15,000	−30,600	
Difference in total costs	−15,600		
Benefits	**Rationale for paying**	**Payment (€)**	**Notes**
Well-functioning drainage and flood mitigation	Farmers pay the costs for ensuring drainage and flow conveyance, equaling the estimated costs of conventional dredging	−15,000	The total cost partitioning can be realized through public funding covering 74% of TSC construction costs
Improved water quality and biodiversity	Public funding covers the difference in total costs as the additional benefits are collective [1]	−15,600	

[1] Additional private funding can be arranged through developing mechanisms for ecological compensation (biodiversity offsetting) or for stakeholder participation according to their willingness to pay.

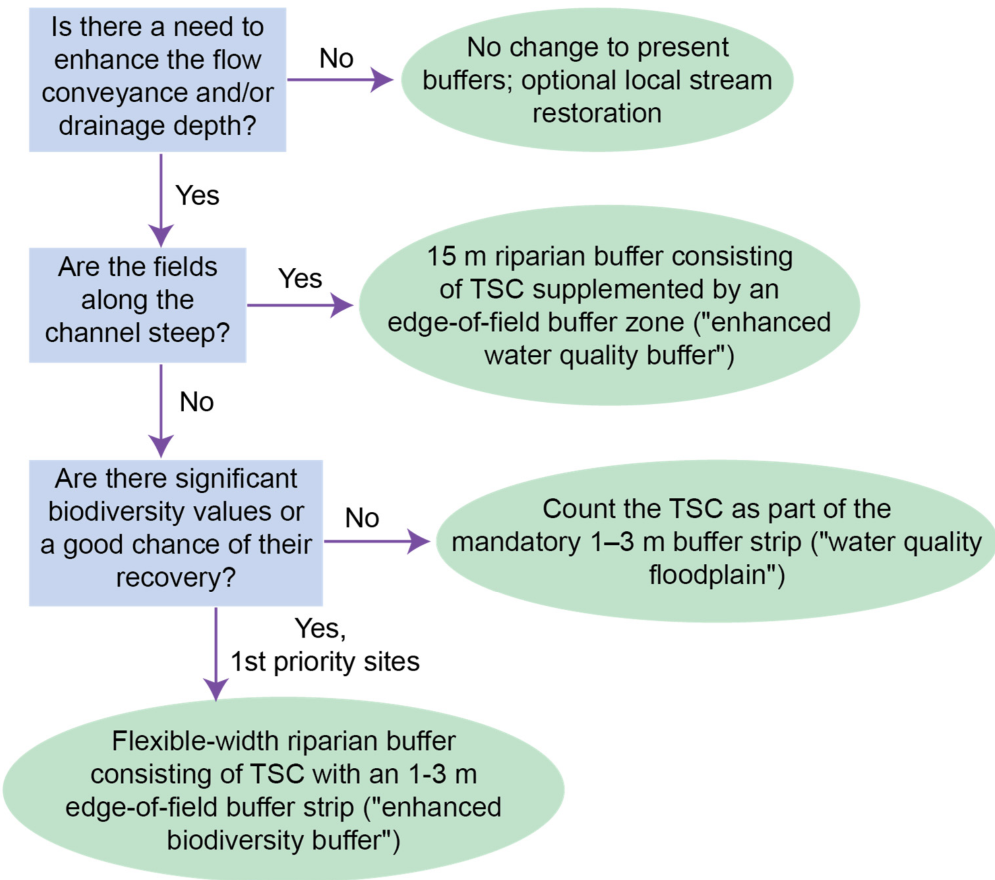

Figure 6. A preliminary decision support tree for the targeting of two-stage channels (TSCs) and the existing vegetated riparian buffers of CAP-AES, as well as their combinations. Focus on small channels as investigated in this study.

We propose that public funding should cover the difference in the total costs between TSCs and conventional dredging (15,600 €/km, Table 5) since the additional benefits are collective, which would make TSCs as appealing as dredging for farmers. In addition, TSCs should be included into the CAP-AES by considering them eligible for the obligatory riparian buffer since TSCs provide comparable benefits as the presently required edge-of-field buffers (Figure 5, Section 4.1). This would largely eliminate the costs associated with lost crops and subsidies caused by the lost field area (Sections 3.3 and 3.4), and would result in TSCs being approximately 2 times more expensive than conventional dredging over a 60-year time frame (Table 5). We acknowledge that the cost difference between conventional dredging and TSCs decreases with the increasing time frame since the high initial construction costs of TSCs are realized only once.

The difference in the total costs can be compensated to the farmers by public funding based on an €/TSC metre approach (15,600 €/km, Table 5). While TSCs are non-easily reversible investments and agro-environmental policies are known to change with time, an initial one-time lump-sum payment would ensure the farmers do not end up paying higher life-cycle costs than with conventional dredging. Another alternative is a lower initial compensation with an agreement, e.g., for annually recurring payments covering the rest of the cost difference over the considered time frame. A lump-sum compensation of 15,600 €/km can be arranged by public funding covering 74% of TSC construction costs (21,200 €/km, Table 5), after which no other compensation is needed over the considered time frame. Using Finland as an example, a re-direction of 1/3 of the €2.5 million/year of the national support for dredging (Section 3.4) to TSCs would increase the rate of publicly supported TSC construction to 53 km/year from the rate of ~2–5 km/year in the past few years and would allow saving the most ecologically important sites from conventional dredging. The present public financing for conventional dredging may be considered as an environmentally harmful subsidy in light of our findings regarding the more favourable environmental performance of TSCs. The subsidized TSC sites should be prioritized by the ELY Centres as the available national funding cannot cover all the sites requiring maintenance. With the proposed reform, farmers would pay 5600 €/km of construction costs for the TSC, i.e., ~10% more compared to the one-time price for conventional dredging without subsidies (5000 €/km). To clarify the financing and the different support systems (Section 3.4), the national MAKERA may be ceased and its funds directed via the CAP-AES.

While the values represent the Finnish cost level, the calculation methodology (Section 2.3.1) can be applied to other countries using their cost data. The financing model suits a governance framework where the landowners along the channel are responsible for the implementation and costs of channel maintenance. In Finland, there has been a deliberate change in the management of the agricultural channels towards much less state control and initiative since the 1990s. We acknowledge that due to historical reasons, EU countries have differing ownership and governance of channels, and thus the TSC approach should be adapted to the local context.

Since public funds are limited, we propose a fast and frugal decision tree for supporting the spatial targeting of TSCs and the existing vegetated buffer measures of the CAP-AES based on the findings of this study (Figure 6). This includes the presently compulsory edge-of-field buffer strips with a minimum width of 1–3 m and the optional 15 m wide edge-of-field buffer zones. The novelty here is the flexible combination of edge-of-field buffers with the after-field type of buffers provided by TSCs, while maintaining the minimum widths of the riparian buffers as in the present CAP-AES.

Public funding to TSCs is primarily recommended for locations with pressing technical problems related to high water tables and flooding (Figure 6). The first priority should be given to sites with pronounced in-stream biodiversity values, for which we propose a conservative approach consisting of TSCs in combination with a minimum of 1 m wide edge-of-field buffer strips to support a richer biodiversity (see Section 4.1). The edge-of-field buffer can be narrower than presently, since the upper floodplain bank provides approximately similar dry habitat. The second priority should be given to reaches with high nutrient loads, for which we recommend to count TSCs into the required total buffer width (Figure 5) due to their expected benefits compared to edge-of-field buffers (Section 4.1).

For flat fields, we propose that the TSC can replace the mandatory 1–3 m edge-of-field buffer strip. For channels with adjacent steeply sloping fields and thus pronounced surface runoff, we recommend combining the TSC with an edge-of-field buffer zone so that their total width equals the presently recommended 15 m. As a novel aspect to enhance the agricultural biodiversity, we encourage allowing shrubs and trees in the buffer areas (e.g., [80]). Finally, for sites without technical problems related to drainage or flooding, the economical solution is to continue with the present edge-of-field riparian buffer strip or zone, which can be combined with optional local restorations if stream biodiversity requires improvements.

The TSC floodplains can be constructed on either one or both sides of the main channel and can be as wide as desired but should have a minimum width of 1 m on each side for achieving benefits. We propose to count the area extending from the top of the floodplain bank to the main channel–floodplain interface as a vegetated buffer in the CAP-AES (Figure 5). In an analogy to narrow trapezoidal channels (Section 3.4), we propose that the eligible area extends to the centreline of the low-flow channel if the width of the low-flow channel is smaller than 3 m. This creates an additional incentive for small streams with up to some tens of km^2 of catchment area where the top width of the existing trapezoidal channel is larger than 3 m, but where the width of the low-flow channel would be $\leq$3 m. The edge-of-field buffers can be compensated according to the same principles as presently for conventionally dredged channels, i.e., counting 1–3 m wide buffer strips into the subsidized field area and making separate agreements for the buffer zones. The proposed reform includes only rather small changes to the existing CAP-AES and is thus likely feasible to implement into the new programme period starting from 2023. The developed financing model is expected to be approximately cost-neutral and more cost-effective than the present system, as it is based on re-targeting existing public funds through substituting less environmentally effective measures with more effective ones. In Finland, political willingness for renewal of the subsidy system was expressed in the latest government's platform of 2019, which set as a target to reduce emissions from the land use sector, as well as to improve water protection and increase the resources for water management.

In addition to private funding from the landowners and public financing, additional private funding could be arranged for TSCs through establishing an ecological compensation (biodiversity or nutrient load offsetting) mechanism [81,82] or through financial support from residents of the surrounding areas or other stakeholders according to their willingness to pay. Ecological compensation could improve the state of fish stocks and biodiversity in rivers and streams, with the restorations of traditional agricultural environments and of drained marshes recommended as examples for Finnish conditions [83]. In addition, compensation could offer business opportunities for farmers. Estimates of the willingness to pay (WTP) can be obtained from a previous primary valuation study about the positive effects of headwater brook restoration and associated improvement in ecosystem services for human welfare in sparsely populated areas in Finland [84]. The households' mean WTP ranged at 17.80–35.30 € per household per year for the combined benefits of improving water quality, biodiversity, and more natural flood cycles. Although conducted in a catchment with 82% forest coverage, this welfare estimate is on the right scale when compared to other measures to improve the state of the aquatic environment in agricultural and rural areas. For instance, establishing constructed wetlands in 10% of the agricultural riparian buffer strips in Denmark was viewed as a positive change, as indicated by a significant mean WTP of 272–461 DKK (36–62 €) per household [85]. In France, on the River Garonne, a resident's WTP for habitat preservation was 35–66 FF (8–14 € as converted from 2002 Francs to 2020 Euros) per person over 5 years [86].

4.3. Future Research Needs and Capacity Building for Mainstreaming Two-Stage Channels

Our literature review (Section 3.1) revealed notable knowledge gaps regarding the performance of TSCs. Regarding the sediment and nutrient retention mechanisms, many studies compared floodplains to conventionally dredged channel beds but did not consider the entire wetted cross-sections. Thus, the processes in the low-flow channel of TSC and banks of conventionally dredged channels, as well as the seasonal effects characteristic for cold climates (Section 3.1), should be better taken into account in the future. In addition, the biodiversity impacts of TSCs require further studies in integration with the physico-chemical channel functioning. Several of the performance indicators (Table 3) were based on expert judgement but should be verified to provide reliable information to policy makers and landowners. Of particular interest to practitioners is the long-term performance of TSCs in providing sufficient conveyance capacity at high flows and the associated need for channel maintenance, such as periodic vegetation cutting. Monetary evaluation of the benefits of NBS is an under-researched topic despite the fact that these approaches are expected to provide several ecosystem services (Table 3).

In addition to developing the financing and governance, capacity building is required for mainstreaming TSCs and other NBS. Scientists should continuously participate in the co-creation and co-development of solutions and methodologies with the key stakeholders as new knowledge and experience are gained. For instance, based on the current scientific understanding, we aim to develop guidelines on TSC design for Northern European conditions. These guidelines are lacking but are clearly needed, as revealed by discussions with consultants designing drainage and flood management solutions. Until then, guidelines developed for the US (e.g., [87]) can be used as a starting point. To support the optimal channel design and maintenance, we propose familiarising consultancies with straightforward physically based methods (e.g., [70]), such as hydraulic models and airborne vegetation mapping, to estimate the influence of different types of channel designs, vegetation conditions, and mowing practices. At the catchment scale, the Ministry of Agriculture and Forestry has proposed creating an operating model for the co-operation of agricultural and forestry sectors and for the piloting of cross-sectoral river basin planning related to drainage [36].

5. Conclusions

The two-stage channel (TSC) design mimicking natural hydro-morphology of lowland streams was deemed a promising new nature-based solution (NBS) for agricultural water management, particularly under climatic conditions requiring drainage. While both conventional dredging and TSCs provide efficient drainage and flood protection, profiting farmers, TSCs offer additional environmental benefits which could be monetised. For instance, the value of water quality improvement through floodplain phosphorus retention exceeded the total costs of TSCs. Our field investigations, one of the first studies on biodiversity in TSCs, indicated positive impacts of the TSC design on plant diversity. Wider implementation of TSCs as after-field type vegetated buffers to targeted areas likely better contributes towards good quality of aquatic ecosystems compared to only the routine application of edge-of-field buffers. Thus, we developed a preliminary decision support tree for the optimal targeting of TSCs with respect to the existing vegetated buffers of the European Union agri-environmental subsidy scheme (CAP-AES, Figure 6). With the TSCs resulting in almost 3 times higher total costs over a 60-year time period according to the present CAP-AES requirements, we propose a reform based on re-targeting EU and national policy and financing. Since the additional improvements in water quality and riverine biodiversity by TSCs are collective benefits, we argue that landowners should be compensated for the additional total costs of TSCs compared to conventional dredging. Firstly, to mitigate the costs caused by lost field area, we propose TSCs to be included into the CAP-AES by considering them eligible for the obligatory riparian buffer (Figure 5). Secondly, to cover the remaining cost difference, we recommend an € per TSC metre compensation for the farmers at priority sites (Table 5). In addition to public funding, innovative sources of private financing should be developed and experimentally tested for NBS with demonstrated performance. To address the significant knowledge gaps, the long-term performance of TSCs including their biodiversity impacts should be investigated through studies allowing real comparisons between TSCs and conventionally dredged reference reaches, including the processes in the low-flow channel of TSCs.

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